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Domestic solar hot water systems: Developments, evaluations and essentials for "*viability*" with a special reference to India

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ABSTRACT

Following typical phases of any technology development, initially there have been research works focusing mainly on the solar hot water systems' (SHWS) technology development then followed by economic aspects. This has resulted in techno-economically feasible standardized solar hot water systems. Owing to these favourable features, SHWS in general and Domestic SHWS (DSHWS) in particular attracted several promotional measures with a view to make them as the alternative for conventional water heating options in India. However, even after the implementation of these measures for more than two decades in India, the potentials-achievements difference remains to be extremely large, the reasons for which are attributed to the so-called "barriers for dissemination". This paper presents a consolidated review of solar water heating related issues covering these technological developments, techno-economics, promotional measures, present dissemination status and barriers for dissemination, all with a special reference to the Indian context. Also presented in this paper is the identified need for "*viability*" studies of DSHWS and "essentials for *viability* evaluations of DSHWS" in multi-dimensional environment that aid in developing decision making tools to improve dissemination of DSHWS.

Contents

1. Introduction

Using the freely available solar energy is an extremely attractive option for low end application like domestic water heating, especially in India which receives a mean daily solar radiation in the range of 5–7 kWh/m^2 with more than 275 sunny days in a year [1]. Solar water heating is cost effective for India and can reduce India's demand for oil, gas and coal if pursued to meet the hot water demand in industry and households [2]. Solar hot water systems (SHWS) are devices that use solar energy to heat water.

A SHWS consists essentially of a collector for solar radiation connected to a storage tank by pipes. Two types of collectors available are "flat plate collectors" and the "evacuated tube collector" while the former being the extensively used one for Domestic SHWS

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(DSHWS) due to the due to their low cost, simple design, higher efficiencies, and longer life span, all factors that also facilitate local production and ease of use. The flat plate collector, with its components viz. collector box; absorber assembly; glass covers; thermal insulation at the appropriate places in the whole assembly, acts like a miniature green house and traps solar radiation as thermal energy and becomes heated as a consequence. For the water in the storage tank to receive this heat, this water is circulated by means of the pipes in and out of the collector by a natural or forced process.

The line diagram of a typical DSHWS and cut section of a flat plate collector used in DSHWS is as shown in Figs. 1 and 2, respectively. As the water in the riser tubes gets heated by "insolation" (the absorption of solar radiation), it flows upwards into the upper header tube and from there into the top of the insulated storage tank, pushing down the colder water at the bottom of the tank through the connecting pipe into the lower header tube. This natural flow of water by a form of convection or thermosyphon process ensures that heat keeps flowing from the fins of the absorber (which has a black coating for better absorption of radiation) into the water contained in the risers. For large systems the length of the pipes connecting the collectors to the tank or tanks becomes so great that the pressure drop across the system makes it impossible to use the thermosyphon process, so that a small electrical pump has to be provided to maintain a forced flow system. The collector is mounted on a horizontal surface, usually a roof, at a slope of 10° greater than the local latitude so that it receives optimum incident solar radiation during the winter months when the hours of sunlight are least. Both the absorber and the storage tank must be well insulated, the former so that the solar radiation received goes entirely into heating the water and the latter so that heat loss from the hot water during both day and night is minimised. The glass cover of the collector ensures that radiation is received by the absorber but very little is lost by it (since glass is opaque to the far infrared radiation emitted by a warm body, the principle of the greenhouse).

The performance of the whole system depends on the choice of materials, the important factors being the thermal conductance of the absorber tubes and fins, the efficacy of the bonding between tubes and fins, the quality of the insulation, and the corrosion resistance of the entire system, bearing in mind that some parts are exposed to water (of variable purity) at moderately high temperatures and most of the others have to withstand sun and humid air. It is relevant to point out here that water supply in India, even in urban areas, is far from free of suspended matter, even grit. Besides, it can, especially if it is taken from an open well or tube well, contain a significant proportion of dissolved salts. Use of this hard water leads to reduction in system performance due to the scales formations in the water passages. Such issues lead to the use of complicated designs having a heat transfer liquid flowing through the collectors which transfers the heat received to the water in the tank via a heat exchanger provided for this purpose.

For a large (non-domestic) SHWS, the design is complicated by such factors as the need for several collectors connected together to the same storage tank, whose capacity, however, need not be equal to the heating capacity per day of the system, since the water is drawn off all round the day. Beyond a capacity of 3000 l per day (LPD), the array of collectors required and the length of pipes needed to serve them cause the thermosyphon process to fail, as was noted above, and electrical pumping is needed to maintain the circulation of the water.

The general requirements for installing a 100 LPD DSHWS include a shadow-free roof or ground area 3 m^2 with sufficient strength to support 200 kg of static load, a constant supply of cold water to maintain continuous functioning of the system, and electricity supply to connect a back-up heater. The most cost-effective way to install a DSHWS is to integrate the collector assembly, cold water supply and piping with the design of a new house under construction. DSHWS can easily be installed in group houses and apartments, especially during construction, if adequate provisions are made for piping, collector assembly and cold-water supply.

As it can be observed from the subsequent sections of this paper, the development of SHWS followed typical phases of any technology development. Initially there have been research works focusing mainly on the SHWS technology development then followed by economic aspects. This has resulted in techno-economically feasible standardized solar hot water systems. Owing to these favourable features, SHWS in general and DSHWS in particular attracted several promotional measures with a view to make them as the alternative for conventional water heating options in India. However, even after the implementation of these measures for more than two decades in India, the potentials-achievements difference remains to be extremely large, the reasons for which are attributed to the so-called "barriers for dissemination". Sections 2 and 3 of this paper present a consolidated review of solar water heating related issues covering these technological developments, techno-economics, promotional measures, present dissemination status and barriers for dissemination, all with a special reference to the Indian context. Sections 4 and 5 of this paper present the identified need for "*viability*" studies of DSHWS and "essentials for *viability* evaluations of DSHWS" in multi-dimensional environment that aid in developing decision making tools to improve dissemination of DSHWS.

2. Overview of DSHWS technology evaluations and developments

Even though, use of solar energy for water heating and other low end applications is centuries old, the SHWS in the present form was designed, developed and investigated initially by Close [3], Bhardwaj et al. [4], Gupta and Garg [5]. The basic unit of SHWS, the flat plate collector, was initially investigated by Hottel and Woertz [6], and Bliss [7]. The performance of the collector in terms of design parameters related to, types of absorber plate were investigated by Mathur et al. [8] and Patil [9]; number and type of glass covers was studied by Whillier [10]; Thickness and type of insulation was studied by Whillier and Saluja [11]; anti-reflective coating on glass cover was studied by Hsieh and Coldewey [12]; heat mirror coating on inner glass as an alternative for selective absorber was investigated by Winegarner [13]; spacing between absorber and inner glass and successive glazings were studied by Nahar and Garg [14]; studies on coatings on absorber plates were taken up by Nahar and Garg [15]. While some of these works concentrated on performance evaluation studies also, there has been innumerable number of works that specifically concentrated on performance evaluations.

2.1. Performance evaluations

Works reported by Nahar [16–18], Nahar and Gupta [19] are among the works on the performance evaluations of SHWS. Performance studies at Allahabad, on a simple collector made from corrugated GI sheet were reported by Bhardwaj et al. [4]. Using the developed computer models, Gupta and Garg [5] predicted the thermal performance of DSHWS by computing absorber plate efficiency factors and solar radiation intensities on tilted surfaces. A large SHWS capable of heating 600 l of water up to 55 °C in winter months at Roorkee was designed and tested for its performance by Garg [20]. Possibilities for minimizing the radiative and convective heat losses from the absorber and back of the collector were explored by Madhusudan et al. [21] by optimizing the absorber to cover glass separation, providing low emissivity surface on the collector's back face and spacing additional reflector supported on glass wool insulation behind the back face. Transient model

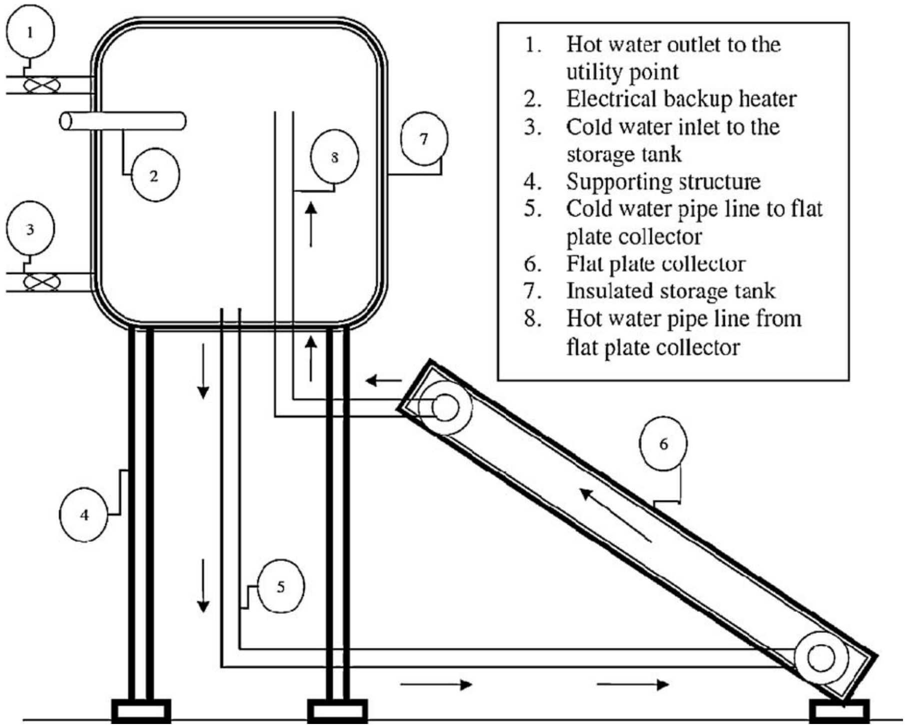

Fig. 1. Line diagram of a typical DSHWS.

for predicting the thermal performance of collector/storage solar water heaters for generalized demand patterns was presented by Kaushik et al. [22]. Similar kind of transient performance analysis for forced circulation solar water heating system with and without heat exchangers in the collector loop and storage tank as well as for SHWS with multiple units connected in series was taken up by Tiwari et al. [23] and Tiwari [24]. Experiments based thermal performance evaluations of flat-plate solar collectors manufactured indigenously in India were reported by Tiwari et al. [25] Based on test results they reported that values of $F_R U_L$ (where F_R is collector's heat removal factor, U_L is the overall heat loss coefficient) for the tested collectors ranges from 5.139 to 7.024. Explicit expression for water temperature as a function of time and space coordinates was evolved by Yadav et al. [26]. The effects of several parameters, such as flow velocity, water depth and the length of the collector on the performance of the system were also addressed in this research work. With the help of experimental data covering water withdrawal rates of 0, 50 and 60 l per hour, on thermosyphonic collector based SHWS at Aligarh, heat transfer and the resulting fluid flow through the collector tubes were studied by Altamush [27]. Design, installation and performance aspects of an industrial model solar water heating system equipped with 2560 m^2 of collector area to heat and supply 110,000 l of hot water at 85 °C per day for an egg powder making plant was presented by Nagaraju et al. [28]. Year round performance and potential of a natural circulation type SHWS was investigated by Nahar [29]. Based on the performance testing, it had been found that (a) the SHWS can provide 100 litres of hot water at an average temperature of 60.6 °C when the tap water temperature is 23.6 °C, (b) it can retain hot water till next day morning at an average temperature of 51.6 °C, and (c) the overall efficiency is 57%. Based on this performance and extended work, it had been concluded that at most places in India, the SHWS can provide 100 l of hot water at an average temperature of 50 °C to 70 °C that can be retained to 40–60 °C till next day morning use. A mathematical solution of the one node transient equation for a flat-plate collector by removing approximations like mean fluid temperature and constant initial temperature used in earlier solutions of the equation was suggested by Dhariwal and Mirdha [30].

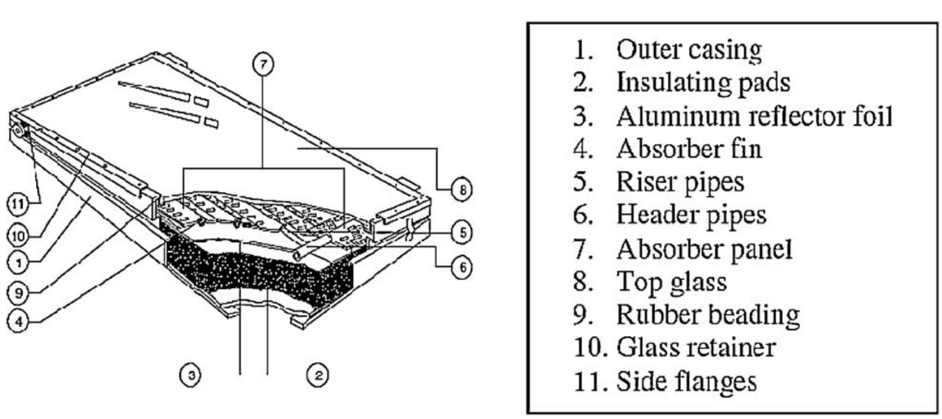

Fig. 2. Cut section of a typical flat plate collector used in DSHWS.

Table 1
Material and specifications of typical DSHWS available in India.[a]

Item description	Materials and specification
Collector	
Absorber	Made of electro grade copper, selectively coated by continuous electroplating of black chrome over nickel substrate on copper sheet of 0.2 mm thickness with heat treatment to withstand temperatures up to 300 °C. Optical properties are absorptivity equal to 0.96 ± 0.02 and emissivity 0.12 ± 0.02, no of fins 9; absorber area 2 square metre
Riser tubes	Copper tube of diameter 12.5 mm ± 0.5, thickness 0.56 mm
Header tubes	Copper tube of diameter 25 mm ± 0.5, thickness 0.71 mm
Bonding between riser and header	Brazing
Bonding between fin and tube	Ultrasonic/TIG welding
Back insulation	Resin bonded rock wool, density 48 kg/m^3, thickness of insulation 50 mm
Side insulation	Polyurethane, thickness of insulation 25 mm
Collector box	100 mm × 25 mm Aluminium channel thickness 1.63 mm
Collector bottom sheet	Aluminium sheet thickness 0.71 mm
Collector stand	Corrosion resistant coated mild steel
Glazing	Single toughened glass, 4 mm thickness with low iron transmissivity greater than 0.85 at normal incidence
Retainer angle for glass	Aluminium angle, size 25 mm × 25 mm × 1.6 mm
All gaskets and grommets	Silicone rubber/EPDM
Collector area and weight	2.132 square metres, 50 kg
Maximum working pressure	6 kg/cm^2
Hot water storage tank	
Material	Stainless steel, AISI 304
Insulation	High density PUF, 50 mm thickness
Outer cladding	Stainless steel
Inter connecting pipe	High pressure steam hose pipe assembly with check nut
Backup heater (electrical)	2 kW
Standing loss of temperature	5–7 °C

[a] As per the brochures of various manufacturers and IREDA leaflets on DSHWS.

Koffi et al. [31] studied theoretical and experimental analysis of a SHWS prototype with an internal heat exchanger made of a rolled copper tube placed diagonally in the storage tank so that the hot fluid crosses a significant mass of stored water. These experimental and theoretical analyses indicate (a) peak heat fluxes of 989 W/m^2, (b) collector outlet water temperature levels of more than 85.5 °C and (c) a collector thermal effectiveness around 58%.

2.2. Modifications and innovations

Simultaneously several attempts were made to modify the existing technologies and to innovate new technologies for water heating using solar energy, though transformation of such deigns in to commercial designs met with a very limited success. Even today, many of the DSHWS systems manufactured and used in India are flat plate based closed loop, thermosyphon based SHWS whose specifications are as mentioned in Table 1.

Design and development of an inexpensive tubular solar collector system, which consists of a spiral-shaped plastic tube coated with a black paint as the solar absorber, was undertaken by Pillai and Agarwal [32]. Water heater utilizing phase change materials for storage of solar energy was proposed and its transient performance analyses were carried out by Bhargava [33]. Numerical calculations to study the effect of a booster mirror, on the performance of a built in storage water heater were presented by Dhiman and Tiwari [34]. Thermal performance studies of an inexpensive underground solar water heater with respect to various parameters were studied by Rai et al. [35], and Dhiman and Tiwari [36]. Kishore et al. [37] studied the performance of portable shallow solar water heater. The authors concluded that these systems can form a major part of potentially low cost DSHWS suitable for middle income groups. Performance analysis of reverse flat plate collector was undertaken by Goel et al. [38] to conclude that the new reverse flat plate design having two absorbers gives the best thermal performance. Soin et al. [39] compared the performance of a two phase water heater with a thermosyphon water heater of identical collector area and storage volume. It was found that the two-phase water heater was 4–8% less efficient than the thermosyphon water heater for clear sky and high radiation levels (22–28 MJ/m^2 day). It was also observed that, in monsoon, two phase heater was 40% less efficient due to low radiation level (12–15 MJ/m^2 day). Built in storage type solar water heater was studied by Prakash et al. [40] by using mathematical models to predict their thermal behavior. The authors claimed that the system performs better under single axis tracking mode as compared to fixed surface mode but the improvement in the performance over single axis tracking is marginal when double axis tracking is employed. A continuous flow type water heater was suggested and experimentally investigated by Venkatesh [41,42]. Through the thermal and experimental analyses carried out, it has been concluded that the performance of the continuous flow type is comparable to thermosyphon type; in Indian context the continuous flow type water heater has more advantages than the thermosyphon flow type water heater in view of its low capital cost and the ease of operation and maintenance. The hybrid photovoltaic and thermal (PVT) collector technology using water as the coolant has been seen as a solution for improving the energy performance in terms of cell efficiency as well as thermal efficiency of the collectors. Possibility of using PVT hybrid systems was attempted by Agarwal and Garg [43], Kalogirou [44], Tiwari and Sodha [45], He et al. [46]. Erdil et al. [47] constructed and tested a hybrid system, composed of a photovoltaic module and a solar thermal collector and proposed that the undesirable heat generated by the PV modules while absorbing the solar radiation may be utilized in water preheating applications. They claimed that the proposed hybrid system produces about 2.8 kWh thermal energy daily while contributing for 11.5% loss in electrical energy generation and they opined that, the low investment cost and the relatively short pay-back period (less than 2 years) make this hybrid system economically attractive.

Use of evacuated tube solar collectors for water heating has also been an interesting research topic in the direction of development of alternate technologies. Works reported by Kim and Seo [48], Morrison et al. [49], Harding and Zhiqiang [50] are among the several works that concentrated on design and performance analyses of these systems. Another development is related to integrated collector-storage (ICS) solar water heaters which are less expensive and can offer the best alternative for domestic applications. Performance studies on different ICS were attempted by Garg et al. [51], Kaushika and Reddy [52], Chaurasia and Twidell [53]. In the global context, research works reported by Mohsen and Akash [54], Smyth et al. [55], Tripanagnostopoulos and Souliotis [56], Sopian et al. [57], Madhlopa et al. [58], Garnier et al. [59] are among the other works that concentrated on theoretical and experimental analyses of ICS solar water heaters. Kumar et al. [60] designed fabricated and tested a truncated pyramid non-tracking type multipurpose domestic solar cooker/hot water system and reported that (a) the system has a maximum efficiency of 54% (b) the system meets the requirement stipulated on two figures of merit as per Bureau of Indian Standards (c) the day-time and average night-time heat-loss coefficients were found to be 5.7 W/°C m^2 and, 3.74 W/°C m^2, respectively, which are comparable to those of flat-plate collector

based solar hot water systems. A portable solar collector and water heater which uses a normal satellite dish of 150 cm diameter as concentrator was designed, built and tested by Badran et al. [61] and found that the device was able to (a) boil 7 kg of water at 20 °C in 1 h, when operated in the bare cooker mode (b) heat 30 kg of water from 20 °C to 50 °C in 2.5 h when operated in collector mode while the highest efficiency in this mode is 77%.

2.3. Testing procedures

Testing methods for SHWS and their applicability for different situations had also been a research concern. A test method for solar water heater system by means of a whole system testing was developed by Kabariti and Mowafi [62] to characterize the thermal behavior for a thermosyphon solar water heating system. A systematic analysis of the contribution of all the uncertainty components on the basis of the ISO 9806-1 test procedure was carried out by Mathioulakis et al. [63] in order to determine the final uncertainty in the instantaneous efficiency of the collector. A critical evaluation of nine dynamic test methods for solar flat-plate collectors was taken up by Nayak and Amer [64]. Based on these comparative studies, sensitivity studies etc., the authors suggested a simple method that could be adopted by manufacturers as an effective tool for the purpose of quality control of their products. Comparison of two test procedures that lead to the elaboration of a set of recommendations for a future revision of test standards, ISO 9459.2 was presented by Carvalho and Naron [65]. Studies to modify the conventional test standards viz. CNS 12557, B7276, by incorporating the heat removal efficiency of the system in addition to the thermal efficiencies during energy collecting phase and system cooling loss during the cooling phase, were reported by Chang et al. [66]. The authors defined an efficiency coefficient, which is a synthesis of characteristic thermal performance and the characteristic heat removal efficiency and suggested that the SHWS should have this new coefficient value greater than or equal to 0.41. Joshi et al. [67] evaluated three standards with the experimental investigations under a wide range of weather and operating conditions on two commercially available SHWS. A sensitivity study had also been carried out in order to examine the effect of measurement errors on the values of the estimated parameters from different standards. The conclusions include (a) there are no significant effects on CNS parameters, (b) JIS is the simplest one to implement (c) the normalizing factor of 20930 kJ/m^2 day for the quantity of heat collected in JIS standard is not very clear, (d) the ISO (part-2) is a very stringent standard as far as the operating and weather conditions are concerned. Based on their observations the authors have suggested that the combination of CNS parameters along with the overnight loss factor of ISO (part-2) forms an ideal set for comparing different thermosyphon type DSHWS. Garcia-Valladares et al. [68] proposed a simple, inexpensive test method to determine the thermal behavior of DSHWS. The authors claimed that the proposed method is capable to determine several performance indicators such as (a) the maximum available volume of water for solar heating, (b) water temperature increment and available thermal energy at the end of the day, (c) temperature profiles and the average temperature in the storage tank, (d) the average global thermal efficiency, (e) water temperature decrement and energy lost overnight, (f) the relationship between hot water volume and solar collector area as function of the average heating temperature, (g) heat losses caused by the reverse flow in the collector loop. Rojas et al. [69] compared the results obtained by applying the EN12975-2 standard, which is a transient method for testing flat plate collectors, with results obtained from the ASHRAE 93 steady-state tests for a well-designed single-glazed selective surface flat-plate collector and found that the collector thermal parameters, $F_R(\tau\alpha)_e$ and $F_R U_L$ (where F_R is collector's heat removal factor, U_L is the overall heat loss coefficient and $\tau\alpha$ represents the product of transmissivity of glass cover and absorptivity of the absorber) obtained by the two test methods are in good agreement. Kaloudis et al. [70] described the operation principle, procedures and then presented the comparative analysis of two ISO standardized tests viz. dynamic method and input–output method for testing the performance of DSHWS.

2.4. Techno-economic evaluations

Consequent to the proven technical feasibility of SHWS, the research community, focused on the techno-economic evaluations of SHWS as a step towards the commercial viability evaluations. Hawlader et al. [71] evaluated the economic viability of SHWS to arrive at the optimum collector area required to meet the hot water needs for a specific application. Energy conservation and pay back periods of SHWS were analyzed by Nahar and Gupta [72] by comparing the performance of a typical SHWS with those of water-heaters using different fuels, viz. firewood, coal, kerosene and electricity. The authors calculated the payback periods by considering compound interest, maintenance cost and inflation in fuel prices and maintenance per year and concluded that the payback periods for solar water-heaters with selective surfaces and single glass covers are 4.09–7.51 years for winter use only and 2.36–4.19 years for year round use. The payback period increases, according to the fuel used, in the sequence firewood, coal, electricity and kerosene. Arguing that, the quantity of ultimate importance is the cost of energy delivered, which has to be optimized along with collector area and storage tank capacity by optimal mixing of conventional energy (by electrical heater or boiler) and non-conventional energy by using solar energy collection devices, Misra [73] developed a simple techno-economic analysis model. Based on the results of the analysis, the author had concluded that, (a) the cost of hybrid energy systems is less than for conventional heating systems, (b) the use of an auxiliary heater inside the storage tank results in wastage of energy due to the larger heat loss from the storage tank because the storage tank is always kept at the desired temperature, and hence, the auxiliary energy consumption is higher (c) use of an auxiliary heater at the load point is economically feasible. Collector assisted solar distillation system as an investment alternative to a solar hot water system was studied by Sinha et al. [74]. Based on the techno-economic analysis, it was concluded that the cost of hot water for a temperature raise in the range of 30–40° is much less than the cost of distilled water. Sinha and Tiwari [75] developed a procedure for assessing the economic viability of a solar water heater in a dynamic economic environment. Based on the calculations made to find the optimum life time for replacement of the system and the payback period for different interest rates and different increases in maintenance, the authors concluded that, (a) the optimum life time of a solar hot water system for replacement decreases with an increase in maintenance cost, (b) the actual life of the system can be increased by increasing the initial maintenance cost without replacement after the optimum life time, (c) the payback period increases with an increase in initial maintenance cost and also with the rate of increase in maintenance cost. Reddy [76] applied engineering economics principles to evaluate the installation of SHWS versus purchasing an electrical heater. With the results of the break even analysis, the author had shown that, (a) the initial cost of SHWS and the electricity price are the two important parameters that determine the choice, (b) to certain extent rate of interest on the loans also affect the choice. Based on the analyses the author concluded that if the rate of electricity tariff increase is greater than the inflation rate then it is financially advantageous to install SHWS. On the other hand if the rate of inflation is greater, then one has to look in to the factors like cost of SHWS, life time, bank interest rate, and the cost of the electric heater before taking a final decision. In an attempt to suggest

Fig. 3. Flat plate collector based solar hot water system.

cost effective SHWS, Nahar [77] compared the techno economics of three solar water heaters having Galvanized Steel–Aluminium fin, Copper–Aluminium fin and Copper–Copper fin in flat-plate collectors. It has been found that performance of all the three heaters is almost similar. The payback period of a solar water heater with G.S.–Al collector has been worked out by considering 10% compound annual interest, 5% maintenance cost, 5%, inflation in fuel prices and maintenance cost. The payback period varies between 2.92 years to 4.53 years depending upon which fuel it replaces. The payback periods are in increasing order with respect to fuels: electricity, firewood, LPG, charcoal, and kerosene. The potential number of Indian households who can invest in DSHWS have been estimated by Chandrasekhar and Kandpal [78], based on the income distribution in the country, the capital cost of solar water heating systems, interest rate charged on the loan provided for the purchase of DSHWS etc. Using the seasonal and diurnal variation of ambient temperatures at many locations in the country, the periods with annual hot water requirement have been identified. While presenting that, in Jordan the demand for SHWS is decreasing because of high initial investment, Kablan [79] presented the economic feasibility of SHWS with that of Gas Geyser System (GGS) whose analysis was carried out by a spread sheet based software developed for the purpose. Through this analysis it was presented that, for Jordan conditions, (a) SHWS is more economical as long as electricity is used to heat water for less than 120 days (b) the optimal operation life for a SHWS in Jordan is 20 years and for a GGS is 7 years.

3. Issues on DSHWS in India

Owing to the developments in the global and Indian contexts as presented in the previous sections, the flat plate based closed loop SHWS has been evolved as one of the promising options for water heating in the domestic sector. Various issues concerning DSHWS in India are as presented below.

3.1. Techno-economic issues

As observed from Fig. 3 which shows a typical DSHWS used in India, all the three main components of SHWS viz. the solar collector, energy transfer system and storage system are integrated together to make the DSHWS as compact as possible. The collector assembly, the heart of any SHWS, can be a flat plate type or an evacuated tube type, the former being the most prominent one. In India where there are high levels of insolation, flat plate collector based thermosyphon closed loop systems are most common in the domestic sector, due to their low cost, simple design, higher efficiencies, and longer life span, all factors that also facilitate local production and ease of use.

Technical specifications of typical flat plate collector based DSHWS available in the market are as given in Table 1. Typical values of thermal efficiencies of these collectors are in the range of 50%. These DSHWS supply 100 l per day (LPD) of hot water in the temperature range of 55 °C to 70 °C depending on the insolation levels and inlet temperature of water and are capable to cater the hot water needs of typical family of four. In order to have uninterrupted hot water supply, a 2 kW immersion heater is provided in the storage tank along with a thermostat to control it. The overall dimensions of the collectors used in these systems vary from 1.8 m × 1.2 m × 0.1 m to 2.12 m × 1.04 m × 0.1 m. The life cycle expectancy of the device is around 15–20 years.

Bureau of Indian Standards (BIS) has been the standardising and certifying agency for the collectors being used for SHWS in India. These standards viz. IS 12933 cover standards for materials; dimensions; workmanship; testing methods such as static pressure leakage tests, outdoor rain penetration tests, thermal performance tests; Instrumentation for testing etc. Currently, the certification is done at six regional test centres supported by Ministry of New and Renewable Energy (MNRE), even though there is a persistent demand from the manufacturers to use the local expertise for certification. List of these test centres is as given in Table 2 [80]. Most of the collectors manufactured in India are in compliance with the standards and specifications, though there are some non-standard models available in markets. As per these standards the collectors being used have $F_R U_L$ values less than or equal to 5.0 W/m^2 K and $F_R(\tau\alpha)$ values greater than or equal to 0.65 [81] (where F_R is collector's heat removal factor, U_L is the overall heat loss coefficient and $\tau\alpha$ represents the product of transmissivity of glass cover and absorptivity of the absorber).

Current prices of DSHWS ranges from Rs. 14,000 to Rs. 22,000 including the plumbing and other overheads, with a payback period of 2–3 years when electricity is replaced [82,83]. As is the case with any Renewable Energy Technology (RET), DSHWS also suffer with initial upfront costs, though the savings realised by replacing the conventional technologies with DSHWS are quite substantial. Table 3 shows approximate likely monetary savings that can be made by using a typical 100 LPD system, for different regions of the country. It may be noted that, the use pattern and savings for southern region pertains to the typical climate of Bangalore, while those for western region relate typically to Pune climate.

3.2. Promotional measures

Organised efforts by India's central government to promote the use of solar thermal energy, particularly in solar water heating systems, began in 1984, when the solar thermal extension programme was established under the Department of non-conventional energy sources, now the Ministry of New and Renewable Energy (MNRE). In an effort to promote the installation of SHWS, during late 1980s, capital subsidies ranging from 30% to 100% were offered to certain categories of users by the then Department of Non-Conventional Energy Sources. Government departments were the major "beneficiaries" of 100% subsidised systems, most of which lay idle for want of appreciation of the value of a SHWS that had cost the user nothing. Such users (or non-users) did not care about the performance of the system [85]. For domestic systems, from Rs. 3000 per system (roughly 30% of system cost) during 1984–1985, the subsidy was cut to Rs. 1000 per square metre of collector area in 1991–1992. For non-domestic systems, it was 75–100% from 1984 to 1985 onwards till it was reduced to 60% in 1988–1989, further cut to 30% in 1990–1991 and brought in line with the subsidy for domestic systems in 1991–1992. In the later years, subsidies are gradually reduced and finally were abolished in July 1993 [86]. Currently, MNRE, which is responsible for development and demonstration of RETs in India, is implementing a soft loan scheme with interest subsidy. Under this scheme, soft loans with an effective maximum interest rate of 5% (2% for domestic users, 3% for institutional users

Table 2
List of test centres for flat plate collectors in India.

S. no.	Test centre	S. no.	Test centre
1.	The Adviser and Head, Solar Energy Centre, Block 14, CGO Complex, Lodi Road, New Delhi 110 003	4.	The Principal Investigator, Regional Solar Energy Testing Centre, School of Energy, Environment and Natural Resources, Madurai Kamraj University, Madurai 625 021
2.	The Head, School of Energy & Environment Studies, Devi Ahilya Vishwavidyalaya, Takshashila Campus, Khandwa Road, Indore 452 017	5.	The Director, School for Energy Studies, Physics Department, University of Pune, Pune 411 007
3.	The Director, Regional Test Centre (Solar Thermal), School of Energy Studies, Jadavpur University, Kolkata 700 032	6.	The Director, Regional Test Centre, Sardar Patel Renewable Energy Institute, P.B. no. 2, Vallabh Vidyanagar 388 120

Source: Ref. [80].

and 5% for industrial/commercial users) are available from Indian Renewable Energy Development Agency (IREDA), more than 10 public sector banks, private sector banks, scheduled cooperative banks, Reserve bank of India (RBI) approved non-banking financing companies, intermediaries of IREDA (manufacturers/suppliers) and other public/private financing institutions [82]. Overall fund management has been entrusted to IREDA. The banks and other financial institutions (FI) are required to provide loans at prescribed rates to beneficiaries and claim interest subsidy (difference between the lending rate of banks/FIs and MNRE prescribed interest rates) from IREDA. As on date, 31 banks and financial institutions are participating in the scheme through their branch network in different parts of the country [82]. The borrowers will be eligible for loan up to 85% of the cost of the systems, repayable over a period of five years. In order to avail these loans, SHWS being financed must utilize BIS approved solar collectors, even though, there is a demand from certain manufacturers (e.g. manufacturers in Bangalore) to extend the loan facilities for both standard and non-standard SHWS. In India, there are more than 60 registered manufacturers producing BIS approved collectors [87]. In addition, capital subsidy is available to builders and developers/development authorities/housing boards/cooperatives/group housing societies for providing solar water heating systems in new buildings and housing/commercial/institutional complexes. The capital subsidy is operated by MNRE through State nodal agencies [82]. In a separate initiative, a model regulation/building bye-law for mandatory installation of SHWS in new buildings was circulated by the ministry of urban development to all states and union territories with a request for onward circulation to all local bodies for incorporation in their building bye-laws. Necessary orders have been issued in 19 States and 41 municipal corporations/municipalities have so far amended their building bye-laws. States like Andhra Pradesh, Madhya Pradesh, Punjab, Himachal Pradesh, Maharashtra, Tamil Nadu, Rajasthan, Haryana, Uttar Pradesh, Uttaranchal, Chandigarh, Chhattisgarh, Nagaland, Delhi, West Bengal, Karnataka, Mizoram, Dadar & Nagar Haveli are emphasizing on amendments in buildings bye-laws. States like Karnataka, Gujarat, West Bengal, Maharashtra, Andhra Pradesh, Uttar Pradesh and Chhattisgarh have amended the building bye-laws [82].

Further to the encouraging measures from the central government, governments in the states such as Uttar Pradesh, Karnataka, West Bengal, Uttarakhand, Assam, Tamilnadu, and Maharastra are taking measures to promote the use of DSHWS by offering additional incentives related to electricity tariffs, rebates on property taxes etc. [88]. For instance, in the year 2005 itself, Thane municipal corporation has announced a rebate of 10% in property tax to users of SHWS [89] where as Uttaranchal has decided to provide Rs. 50/- per month as rebate in the electricity tariff to users of solar water heaters. Interest free loans are available to domestic users in the North-Eastern States, Sikkim, Himachal Pradesh, Islands, J&K, Uttarakhand, Chattisgarh and Jharkhand [82].

The Jawaharlal Nehru National Solar Mission (JNNSM) (which was launched in January 2010) is a major initiative of the government of India and state governments to promote ecologically sustainable growth while addressing India's energy security challenge. The mission includes major programme titled "The below 80 °C challenge – solar collectors" for solar thermal technology with an objective of achieving the ambitious target of ensuring that applications, domestic and industrial below 80 °C, are solarised. As per the mission, the deployment of SHWS has been divided into three phases. The target of 7 million square metres has been set for phase I (financial year 2010–2013); 15 million square metres for phase II (financial year 2013–2017) and 20 million square metres for phase III covering period (financial year 2017–2022) [90].

3.3. Present dissemination status

According to the conservative estimates the potential for the deployment of solar water heaters in the country is around 140 million square metres of collector area [82,91]. There are 45 million potential households for the installation of DSHWS [91].

Cumulative growth of SHWS in terms of collector areas installed is 0.119 million square metres in 1989–0.68 million square metres by the end of 2002 [86]. By the end of year 2004 a total of 0.8–0.9 million square metres of collectors have been installed [82,91,92]. The growth trend in the recent past, as per the statistics of MNRE, is as shown in Fig. 4. As per MNRE statistics, by June 2010, the cumulative achievement is 3.53 million square metres [92]. However, it is not clear what fraction of the above mentioned figures corresponds to domestic sector. According to conservative estimates, 80% of the collectors installed are in the commercial and Industrial sector [93]. Also, these statistics represent cumulative growths and not the systems which are in actual use. The systems in actual use, serving their intended purpose, may be lesser.

Table 3
Expected electricity and monetary savings from a 100 LPD DSHWS.

	Northern region	Eastern region	Southern region	Western region
Expected no. of days of use per year	200	200	250	250
Expected yearly electricity saving with use of full capacity, kWh	950	850	1200	1300
Monetary savings at different prices of electricity, Rs/year				
Rs. 4/kWh	3800	3400	4800	5200
Rs. 5/kWh	4750	4250	6000	6500
Rs. 6/kWh	5700	5100	7200	7800

Source: Ref. [84].

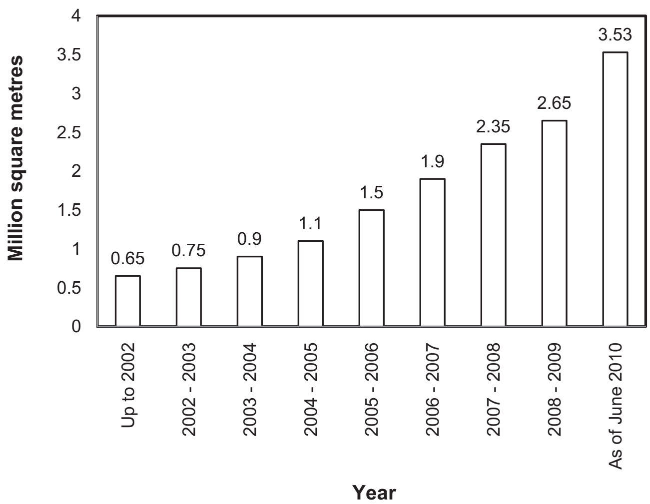

Fig. 4. Cumulative growth of SHWS in terms of collector area installed [82].

These low growth statistics and the resulting vast potential-achievements difference, the excessive dependence on conventional energy resources for all the domestic energy needs including the low end application of water heating, calls for the studies that address the reasons for this low dissemination. An attempt to review the available literature on this topic will reveal that there is a dearth of such studies. However, in the recent past there are few works, that specifically addressed these issues for RET in general and few other specific RETs. These works and few works specific to SHWS in India and in other countries are useful in understanding the key issues on barriers for dissemination of DSHWS.

3.4. Issues on barriers for dissemination

One of the earliest evaluations that addressed the constraints for the barriers of dissemination of SHWS was reported by Painuly et al. [94]. In their analysis, the authors studied the energy consumption for domestic hot water (DHW) for various economic income classes in India. The percentage of households using DHW was seen to be nearly constant at 70% across all income classes. The amount of conventional energy being used for domestic hot water that could be replaced by SHWS was estimated. The authors obtained limits on prices of practical DHW equipment for wide-scale use in India by using the market value of energy spent on DHW and found that, independent of the fuel mix, the cost of DHW per litre remains the same. In the detailed stakeholders' survey based study, Reddy [95] studied the costs and benefits, importance of various policies, level of awareness to understand the barriers for the dissemination of various RETs, including SHWS, in Maharastra. Specific to SHWS, the study was conducted by taking the interviews from 80 household of two urban areas in Maharastra. From the information collected on the appliances used for water heating, it was identified that more than 93% of the households depend on Electric geysers, gas stoves, kerosene stoves and SHWS for water heating. Based on the analysis of the perceptions obtained through the survey, the author identified that, (a) high initial cost, (b) non-reliability of SHWS to supply hot water in required quantities and at required temperatures, (c) no noticeable savings in electricity, (d) non-availability, are the main reasons for not using SHWS. Similar results were reported by Reddy and Painuly [96] based on the results of the barriers' analyses done using the data obtained from the household surveys conducted in Bombay and Pune. The authors observed that (a) although 33% of the SHWS users were dissatisfied with the performance of the equipment, barriers related to technical issues play a less significant role, (b) development and dissemination of solar energy technologies in India has been aided by provision of variety of financial and fiscal incentives such as capital subsidy, low interest loan and accelerated depreciation related income tax benefits to the users on the purchase of solar energy technologies. Claiming that there is a spectacular diffusion of solar energy use for domestic hot water production in Greece, Sidiras and Koukios [97] reported that, major barriers for the diffusion are economic i.e. high initial cost, long payback time, not owner ship and other spending priorities. The major driving forces were reported to be a mixture of socio-economic nature such as (a) reduction of hot water cost, (b) self-sufficiency, (c) comfort and quality of life. They recognized environmental factors also to be the driving force even though, currently, their importance level is low. Through the exemplifying evaluations of financial and fiscal promotional measures effective in India, Chandrasekhar and Kandpal [98] attempted to determine the effective capital cost of solar energy technologies to the user. The authors found that, in the case of DSHWS, 40% capital subsidy is much better than a provision of a loan (80% of the capital cost) at 5% for a period of 5 years. It was concluded by the authors that the provision of income tax benefit on the amount of investment made by the user on the purchase and installation of RET is likely to be more useful than the provision of low interest loan, to attract the high income and upper middle income groups of the country. While tracking down the supportive measures necessary to incubate, sustain and grow the solar water heating industry, Sunderasan [99], opined that (a) appropriate financial aid is the key to help mainstream the solar thermal technology employed in water heating, (b) nature, amount and application of such funding are dictated by the relative maturity of the industry, (c) making available subsidized funding to a mature market is as superfluous and counterproductive as providing consumer finance at the product demonstration stage, (d) it is absolutely mandatory for the ministries and enabling agencies to distance themselves as the industry matures to allow the "invisible hand" of the market to take control. Through an opinion survey based assessment of RETs development in India, Chandrasekhar and Kandpal [91] attempted to identify the barriers for the dissemination of DSHWS and other RETs. While presenting some broad directions only, (due to relatively small size of respondents), the authors summarized that more than 50% of the respondents rated resource availability, appropriateness of the technology, financial and economic viability, energetic feasibility, environmental sustainability, institutional preparedness, awareness and user's training, availability of after sales and services etc., as very important to extremely important barriers for the promotion of DSHWS.

In addition to the above mentioned works that specifically concentrated on barriers for dissemination of SHWS, works on the barriers for the dissemination of various RETs are also helpful in identifying the key issues governing the dissemination of SHWS. Works reported by Rannels [100], Tsoutsos [101], Athanassios and Sevastianos [102], Tsoutsos and Stamboulis [103] are among the works that concentrated on the evaluations on current status, success and/or barriers for the dissemination of various RETs in different countries. In the Indian context, works reported by Rao and Ravindranath [104] and Ghosh et al. [105] on policies to overcome the barriers for bio energy, Gupta [106] on roles of various RETs in generating sustainable livelihoods, Pohekar et al. [107] on wind energy developments, Pohekar et al. [108] on dissemination of cooking alternatives, Pohekar and Ramachandran [109,110] on hierarchical approaches on promotion and utility of solar parabolic cookers, Malhotra et al. [111] on participatory processes on designing cooking energy programmes with women, are among the works that concentrated on the dissemination of different RETs. Arguing that there are several barriers that impede the penetration of RETs, Painuly [112] proposed a framework to identify and overcome the

barriers. The author had suggested that there are seven barrier categories viz. market failure/imperfections, market distortions, economic and financial, institutional, technical, social, cultural and behavioural and finally the miscellaneous category, with each category containing several sub elements, most of which are common to all RETs. The depth and direction of elements of each category vary across the RETs and countries. While suggesting the frame work, the author emphasized the importance of literature review, site visits, and views of stakeholders in identifying the barriers and the measures to overcome them.

4. Pointers towards the need for "*viability*" evaluations

The above presented discussions on developments, evaluations on solar water heating technology and the Indian energy scenario suggest the following points towards the need for "*viability*" evaluations.

1. In the stages of technology development cycle, SHWS technology is highly successful in crossing incubation and growth stages as observed from the works reported on technology development, test standards, performance evaluations, alternate technologies etc.
2. Excessive dependence on conventional energy resources for all the domestic energy needs including the low end application of water heating, the vast potentials-achievements difference for SHWS coupled with well proven techno-economic feasibilities of these SHWS etc. suggest that the there is a definite need for the studies that address the reasons for the low dissemination to evolve strategies for improving the dissemination of SHWS, at least in the sectors where the scope for such a dissemination is high. The ever increasing urbanisation, increased economic growth, higher economic affordability, increased urge to have sophisticated life styles, increased energy demand qualify the domestic sector in urban India to be the promising area for such studies.
3. There have been attempts to investigate the barriers for making SHWS a main stream product/technology. Most of the works perceived techno-economics as the main barrier and worked on to prove that the SHWS are techno-economically viable. Historically, these attempts followed "*defensive approach*" to prove that SHWS are techno-economically viable.
4. The dissemination studies and frame works reported on SHWS and other RETs suggest that the barriers for the dissemination of RETs in general and SHWS in particular are multi-dimensional in nature, with each of the dimensions containing several elements of barriers (criteria for the barriers) pertaining to technical, economical, social, behavioural, market issues.
5. Of late there are few works that addressed the multi-dimensional, multi-criteria nature of the problem of analysis of barriers for the dissemination of the SHWS. However, these works considered the SHWS in isolation, without considering the effects of other water heating options available in the market. The reported works addressed only few of the barriers and did not consider these multi-criteria in comprehensive manner to study their collective effect.
6. Perceptions of consumers and other stakeholders on a particular option/technology play a vital role in the dissemination of any RET in general and DSHWS in particular. Very few works, that involved the stakeholders' opinions in studying the barriers for the dissemination, were reported. A comprehensive study that amalgamates the stakeholders' perceptions on several parameters that have a bearing on the dissemination is essential for the better dissemination of DSHWS. There is a dearth of such studies.
7. Under these circumstances, a comprehensive study, that addresses the above limitations would be helpful to revisit the existing dissemination strategies to overcome consumers' inertia in opting for this well proven technology.

5. Essentials for the "*viability*" of DSHWS

In simplest terms, the main reason for low dissemination of DSHWS could be viewed as the perceived notion among the end users that "DSHWS are not viable compared to the other available alternative domestic water heating options". This necessitates the definition and evaluation of the "*viability*" of water heating options. One water heating option is said to be more "*viable*" compared to the other when that option is capable of serving its intended purpose of supplying hot water while satisfying a wide variety of criteria belonging to various dimensions of "*viability*". In this context, a "Dimension" can be defined as a group of several elements of same category which have a direct or indirect bearing on the "*viability*". The so-called "barriers for dissemination" that impede the broader adoption of any water heating option are useful in defining the dimensions and elements that make the dimensions.

The technical incompetence of any water heating option, in terms of several elements such as the efficiency of the water heating process, the quality of various components, the sophistication levels, operation and maintenance, the usable life of the device, reliability levels, ease of installation and use etc., is one of the strong barriers for the dissemination.

In addition, economic barriers are another set of significant contributors for the low dissemination of water heating options especially for the options like DSHWS. It is less expensive for homeowners to opt for the water heating systems which need low upfront costs (e.g. conventional water heaters) than to opt for costly systems (e.g. DSHWS). In addition, many of those who would consider borrowing money to pay the high upfront cost for equipment may not be able to do so, may be due to the barriers arising out of high interest rates involved. Low fuel/energy costs, operation and maintenance costs coupled with direct/indirect subsidies of competing options can also perpetuate the low demand for a particular option and this further marginalizes that particular option.

Prevailing market situations also may hinder growth of a particular option in the markets. With certain class of water heaters (e.g. conventional water heaters) overwhelmingly dominating the market, consumers wishing to adopt other class of water heaters (e.g. SHWS) often encounter difficulty in finding retail outlets or system design and installation businesses with adequate knowledge to properly size, install, and maintain such non-conventional water heaters. Underdeveloped linkages between the various par-

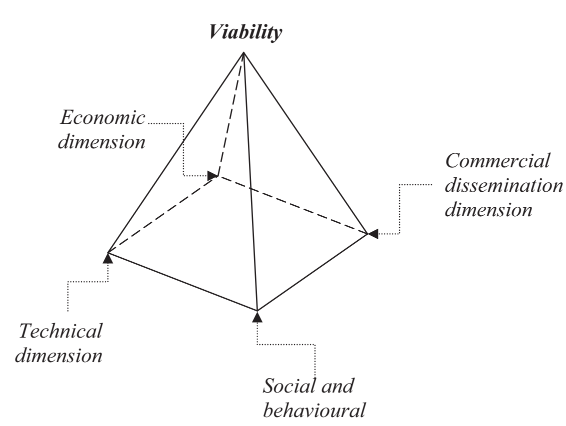

Fig. 5. Water heating options viability pyramid.

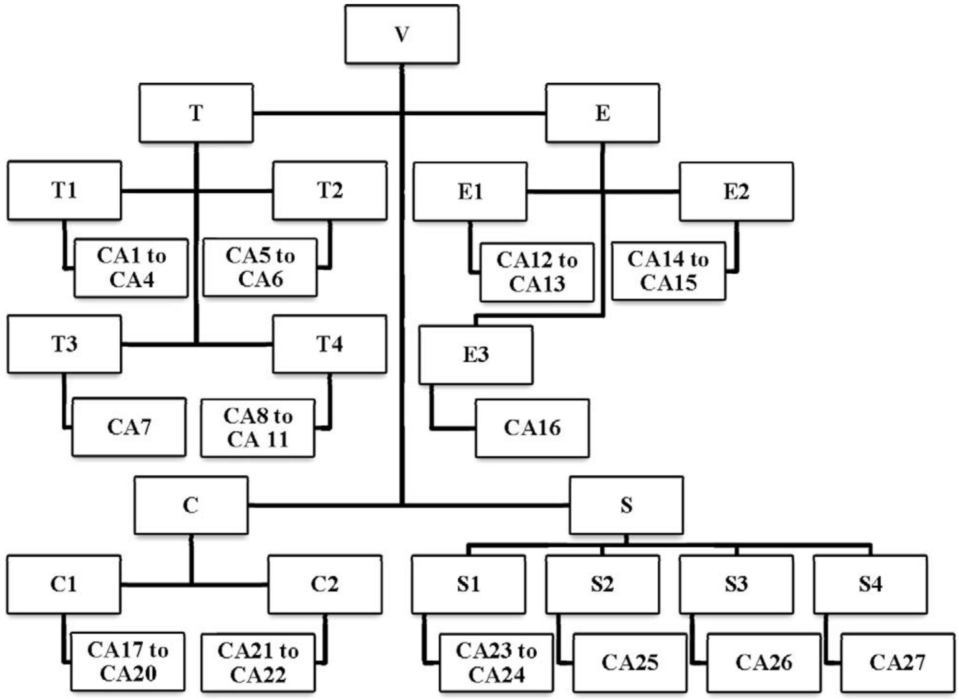

Fig. 6. Hierarchy of criteria for viability evaluation. V, viability; T, technical dimension; E, economic dimension; C, commercial dissemination dimension; S, social and behavioural dimension; T1, device design and performance criteria; T2, device quality and sophistication criteria; T3, site dependent criteria; T4, usage criteria; E1, initial costs related criteria; E2, running costs related criteria; E3, subsidies to consumers; C1, market criteria; C2, policy criteria; S1, residence dependent criteria; S2, aesthetics and appealing value; S3, safety level of the option; S4, individual motivation to go for the option; CA1, compactness of the device; CA2, fuel/energy consumption rate; CA3, usable life of the device; CA4, device ranges; CA5, overall quality of the device; CA6, sophistication level of the device; CA7, reliability of the device; CA8, environmental pollution during actual use of the device; CA9, ease of "installation and use" of the device; CA10, operation and maintenance of the device; CA11, use of the device for other purposes; CA12, initial cost of the device; CA13, interest rates on borrowed finances; CA14, energy costs; CA15, operation and maintenance costs; CA16, subsidies to consumers; CA17, warranties on the device; CA18, brand status of the device; CA19, supply channels; CA20, after sales service; CA21, influence of environmental regulations in choosing the option; CA22, influence of awareness policies in choosing the option; CA23, restrictions from "house owner ship" to go for the option; CA24, restrictions from "house type" to go for the option; CA25, aesthetics and appealing value; CA26, safety level of the option; CA27, individual motivation to go for the option.

ties involved in the industry and little or no coordination between the public and private sectors could also hinder the effective promotion of such non-conventional water heaters. Warranties on the devices, brand status of the devices, influence of various policies in choosing a particular option etc. are also among the various elements that contribute for the "*viability*" for a particular option.

Another important issue is the public perception of bad reputation about a certain class of water heating options. Even when the equipment is of high quality, there could be a public perception that the technology behind the equipment is inherently flawed and not worth serious consideration as a viable alternative to the competing water heating options. Such issues reduce the individuals' motivation to go for the option. Added to this could be the restrictions created by the social groups such as house owners, type of the house etc. for the broader adoption of a particular option.

From the above discussions it can be learnt that, specific to domestic water heating in general and DSHWS in particular, the dimensions of "*viability*" could be technical, economical, commercial dissemination, social and behavioural, with each of these four dimensions having their own characteristic features, such as different elements, different logics, different influences, different regulatory mechanisms etc. Accordingly, the "*viability*" of any water heating option can be seen as a pyramid (Fig. 5) with the four corners of its base being these four dimensions.

The first step in arriving at the "*viability*" of any water heating system in general and DSHWS in particular, using these dimensions is, to arrive at all the constituent criteria of the "*viability*" and then grouping them in to different sub-groups, main groups and then finally in to dimensions. As mentioned earlier, the so-called "barriers for dissemination" that impede the broader adoption of any water heating option are useful in defining these constituent criteria. In a more generic sense, the hierarchy of criteria that can be used to define and hence evaluate the "*viability*" of any water heating option in general and DSHWS in particular is as shown in Fig. 6.

As it can be observed from the "*viability*" pyramid and hierarchy (Figs. 5 and 6), the process of arriving at the "*viability*" of any water heating option in general and DSHWS in particular is a multi-criteria optimization process for interdependent, interacting goals defined by all the elements of the four dimensions of the "*viability*". Based on the above and also based on the basic definition of decision problem given as, "a decision problem exists, if there is a set of options among which one has either to choose the best one, select a set or to produce a ranking" [113], it can be concluded that evaluation of DSHWS to determine its "*viability*" *vis-à-vis* other competing options can be viewed as a multi-criteria decision problem. Multi-criteria evaluation (MCE) techniques can be considered as the tools for solving such multi-criteria decision problems.

6. Conclusions

Review of the available literature on the developments and dissemination levels reveals that the DSHWS are not disseminated in the Indian households to the extent they should be, even though (a) techno-economics are conducive and (b) there have been measures in place for promoting the use of these DSHWS, thereby prompting for defining and evaluating "*viability*" of DSHWS *vis-à-vis* other competing options. This review exercise reveals that, a multitude of barriers that impede the adoption of DSHWS may be considered as the elements of various dimensions of "*viability*" to evaluate

the "*viability*" through multi-criteria evaluation techniques so as to evolve strategies for improving the dissemination of DSHWS.

References

[1] Mani A, Rangarajan S. Solar radiation over India, New Delhi. Allied Publishers Private Limited: New Delhi; 1982.
[2] IEP. Integrated energy policy report of the expert committee. New Delhi: Planning Commission, Government of India; 2006.
[3] Close D. The performance of solar water heaters with natural circulation. Sol Energy 1962;6:33–40.
[4] Bhardwaj RK, Gupta BK, Prakash R. Performance of a flat-plate solar collector. Sol Energy 1967;11(3–4):160–2.
[5] Gupta CL, Garg HP. System design in solar water heaters with natural circulation. Sol Energy 1968;12:163–82.
[6] Hottel H, Woertz B. Performance of flat-plate solar-heat collectors. Trans ASME (Am Soc Mech Eng); (United States) 1942;64:91–104.
[7] Bliss RW. The derivations of several plate efficiency factors useful in the design of flat-plate solar heat collectors. Sol Energy 1959;3:55–61.
[8] Mathur KN, Khanna ML, Davey TN, Sun SP. Domestic solar water heaters. J Sci Ind Res 1959;A18:51–8.
[9] Patil PG. Field performance and operation of a flat-glass solar heat collector. Sol Energy 1975;17:111–7.
[10] Whillier A. Plastic covers for solar collectors. Sol Energy 1963;7:148–51.
[11] Whillier A, Saluja G. Thermal performance of solar water heater. Sol Energy 1965;9:21–6.
[12] Hsieh CK, Coldewey RW. Study of thermal radiative properties of antireflection glass for flat-plate solar collector covers. Sol Energy 1974;16:63–72.
[13] Winegarner RM. Heat mirror – a practical alternative to the selective absorber. In: Sharing the Sun: solar technology in the seventies: proceedings of the conference in American section of ISES and SES of Canada, vol. 6. 1976. p. 339–48.
[14] Nahar NM, Garg HP. Free convection and shading due to gap spacing between an absorber plate and the cover glazing in solar energy flat-plate collectors. Appl Energy 1980;7:129–45.
[15] Nahar NM, Garg HP. Selective coatings on flat-plate solar collectors. Renew Energy Rev J 1981;3:37–51.
[16] Nahar NM. Energy conservation and field performance of a natural circulation type solar water heater. Energy 1984;9:461–4.
[17] Nahar NM. Performance and testing of a natural circulation solar water heating system. Int J Ambient Energy 1988;12:149–54.
[18] Nahar NM. Energy conservation and payback periods of natural circulation type solar water heaters. Int J Energy Res 1992;26:445–52.
[19] Nahar NM, Gupta JP. Performance and testing of improved natural circulation type solar water heater in arid areas. Energy Convers Manage 1987;27:29–32.
[20] Garg HP. Design and performance of a large-size solar water heater. Sol Energy 1973;14:303–12.
[21] Madhusudan M, Tiwari GN, Hrishikeshan DS, Sehgal HK. Optimization of heat losses in normal and reverse flat-plate collector configurations: analysis and performance. Energy Convers Manage 1981;21:191–8.
[22] Kaushik ND, Bansal PK, Kaushik SC. Transient behaviour of collector/storage solar water heaters for generalised demand patterns. Appl Energy 1982;12:259–67.
[23] Tiwari GN, Garg HP, Husain MS. Transient analysis of parallel plate forced circulation solar water heating system. Energy Convers Manage 1984;24:171–5.
[24] Tiwari GN. Transient performance of a thermosyphon water heating system with n-units connected in series. Sol Energy 1985;35:371–5.
[25] Tiwari RC, Kumar A, Gupta SK, Sootha GD. Thermal performance of flat-plate solar collectors manufactured in India. Energy Convers Manage 1991;31:309–13.
[26] Yadav YP, Prasad YN, Yadav AK. Water temperature as a function of time and space coordinate in a collection-cum-storage solar water heater. Energy Convers Manage 1994;35:805–13.
[27] Altamush SM. Heat transfer and fluid flow studies in the collector tubes of a closed-loop natural circulation solar water heater. Energy Convers Manage 1997;38(8):799–812.
[28] Nagaraju J, Garud SS, Kumar KA, Rao MR. 1 MWth industrial solar hot water system and its performance. Sol Energy 1999;66:491–7.
[29] Nahar NM. Year round performance and potential of a natural circulation type of solar water heater in India. Energy Build 2003;35:239–47.
[30] Dhariwal S, Mirdha U. Analytical expressions for the response of flat-plate collector to various transient conditions. Energy Convers Manage 2005;46:1809–36.
[31] Koffi PM, Andoh HY, Gbaha P, Touré S, Ado G. Theoretical and experimental study of solar water heater with internal exchanger using thermosiphon system. Energy Convers Manage 2008;49:2279–90.
[32] Pillai P, Agarwal R. Tubular solar collector. Appl Energy 1980;6:125–32.
[33] Bhargava AK. A solar water heater based on phase-changing material. Appl Energy 1983;14(3):197–209.
[34] Dhiman NK, Tiwari GN. Effect of a booster mirror on the performance of a 'built-in' storage solar water heater. Appl Energy 1983;13:255–64.
[35] Rai SN, Tiwari GN, Bhushan C. An underground water heater with a thermal trap cover on the upper surface of the ground. Energy Convers Manage 1986;26:43–50.
[36] Dhiman NK, Tiwari GN. Effect of movable insulation on the performance of ground collector. Energy Convers Manage 1984;24:107–14.
[37] Kishore VV, Ranga Rao VV, Raman P. A portable shallow solar pond water heater. Solar Wind Technol 1987;4:201–4.
[38] Goel V, Chandra R, Raychaudhuri BC. A study on the performance of a two-absorber reverse flat-plate collector. Energy Convers Manage 1987;27:335–41.
[39] Soin RS, Raghuraman S, Murali V. Two-phase water heater: model and long term performance. Sol Energy 1987;38:105–12.
[40] Prakash J, Garg HP, Hrishikesan DS. Effect of tracking on the performance of a built-in-storage type solar water heater. Solar Wind Technol 1988;5:433–40.
[41] Venkatesh A. Domestic solar water heater – continuous flow type. Energy Convers Manage 1991;32:71–6.
[42] Venkatesh A. Experimental observations on a continuous flow type domestic solar water heater. Energy Convers Manage 1994;35:1041–8.
[43] Agarwal RK, Garg HP. Study of a photovoltaic–thermal system – thermosyphonic solar water heater combined with solar cells. Energy Convers Manage 1994;35:605–20.
[44] Kalogirou S. Use of TRNSYS for modelling and simulation of a hybrid pv–thermal solar system for Cyprus. Renew Energy 2001;23:247–60.
[45] Tiwari A, Sodha MS. Performance evaluation of hybrid PV/thermal water/air heating system: a parametric study. Renew Energy 2006;31:2460–74.
[46] He W, Chow T, Ji J, Lu J, Pei G, Chan L. Hybrid photovoltaic and thermal solar-collector designed for natural circulation of water. Appl Energy 2006;83:199–210.
[47] Erdil E, Ilkan M, Egelioglu F. An experimental study on energy generation with a photovoltaic (PV)-solar thermal hybrid system. Energy 2008;33.
[48] Kim Y, Seo T. Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube. Renew Energy 2007;32: 772–95.
[49] Morrison GL, Budihardjo I, Behnia M. Water-in-glass evacuated tube solar water heaters. Sol Energy 2004;76:135–40.
[50] Harding GL, Zhiqiang Y. Thermosiphon circulation in solar water heaters incorporating evacuated tubular collectors and a novel water-in-glass manifold. Sol Energy 1985;34:13–8.
[51] Garg HP, Avanti P, Datta G. Development of nomogram for performance prediction of integrated collector-storage (ICS) solar water heating systems. Renew Energy 1998;14:11–6.
[52] Kaushika ND, Reddy KS. Thermal design and field experiment of transparent honeycomb insulated integrated-collector-storage solar water heater. Appl Therm Eng 1999;19:145–61.
[53] Chaurasia PB, Twidell J. Collector cum storage solar water heaters with and without transparent insulation material. Sol Energy 2001;70:403–16.
[54] Mohsen MS, Akash BA. On integrated solar water heating system. Int Commun Heat Mass 2002;29:135–40.
[55] Smyth M, Eames PC, Norton B. Heat retaining integrated collector/storage solar water heaters. Sol Energy 2003;75:27–34.
[56] Tripanagnostopoulos Y, Souliotis M. Integrated collector storage solar systems with asymmetric CPC reflectors. Renew Energy 2004;29:223–48.
[57] Sopian K, Syahri M, Abdullah S, Othman MY, Yatim B. Performance of a non-metallic unglazed solar water heater with integrated storage system. Renew Energy 2004;29:1421–30.
[58] Madhlopa A, Mgawi R, Taulo J. Experimental study of temperature stratification in an integrated collector-storage solar water heater with two horizontal tanks. Sol Energy 2006;80:989–1002.
[59] Garnier C, Currie J, Muneer T. Integrated collector storage solar water heater: temperature stratification. Appl Energy 2009;86:1465–9.
[60] Kumar N, Chavda T, Mistry HN. A truncated pyramid non-tracking type multipurpose domestic solar cooker/hot water system. Appl Energy 2010;87:471–7.
[61] Badran AA, Yousef IA, Joudeh NK, Hamad RA. Portable solar cooker and water heater. Energy Convers Manage 2010;51:1605–9.
[62] Kabariti M, Mowafi Y. Testing and evaluation of thermosyphon solar water heating system by means of components testing and whole system testing and simulation in Jordan. Renew Energy 1996;9:A594.
[63] Mathioulakis E, Voropoulos K, Belessiotis V. Assessment of uncertainty in solar collector modeling and testing. Sol Energy 1999;66:337–47.
[64] Nayak JK, Amer EH. Experimental and theoretical evaluation of dynamic test procedures for solar flat-plate collectors. Sol Energy 2000;69: 377–401.
[65] Carvalho MJ, Naron DJ. Comparison of test methods for evaluation of thermal performance of preheat and solar-only factory made systems. Sol Energy 2001;69(Suppl.):145–56.
[66] Chang JM, Leu JS, Shen MC, Huang BJ. A proposed modified efficiency for thermosyphon solar heating systems. Sol Energy 2004;76(6):693–701.
[67] Joshi SV, Bokil RS, Nayak JK. Test standards for thermosyphon-type solar domestic hot water system: review and experimental evaluation. Sol Energy 2005;78:781–98.
[68] Garcia-Valladares O, Pilatowsky I, Ruiz V. Outdoor test method to determine the thermal behavior of solar domestic water heating systems. Sol Energy 2008;82:613–22.
[69] Rojas D, Beermann J, Klein SA, Reindl DT. Thermal performance testing of flat-plate collectors. Sol Energy 2008;82:746–57.
[70] Kaloudis E, Caouris YG, Mathioulakis E, Belessiotis V. Comparison of the dynamic and input–output methods in a solar domestic hot water system. Renew Energy 2010;35:1363–7.

[71] Hawlader M, Ng K, Chandratilleke T, Sharma D, Kelvinkoay H. Economic evaluation of a solar water heating system. Energy Convers Manage 1987;27:197–204.
[72] Nahar NM, Gupta JP. Energy conservation and payback periods of collector-cum-storage type solar water-heaters. Appl Energy 1989;34:155–62.
[73] Misra R. Techno-economic optimization of thermosyphonic solar hybrid water heating systems. Energy Convers Manage 1994;35:205–17.
[74] Sinha S, Kumar S, Tiwari GN. Active solar distillation system – an investment alternative to a solar hot water system. Energy Convers Manage 1994;35:583–8.
[75] Sinha S, Tiwari GN. Techno-economic evaluation of a solar hot water system. Energy 1994;19:479–87.
[76] Reddy BS. Electrical vs solar water heater: a case study. Energy Convers Manage 1995;36:1097–106.
[77] Nahar NM. Capital cost and economic viability of thermosyphonic solar water heaters manufactured from alternate materials in India. Renew Energy 2002;26:623–35.
[78] Chandrasekhar B, Kandpal TC. Techno-economic evaluation of domestic solar water heating systems in India. Renew Energy 2004;29(3):319–32.
[79] Kablan MM. Techno-economic analysis of the Jordanian solar water heating system. Energy 2004;29:1069–79.
[80] MNRE. Test centres for solar thermal devices and systems. Ministry of New and Renewable Energy, Government of India; 2010, http://www.mnre.gov.in/list/test-centres-solartds.
[81] BIS. Solar flat plate collector – specifications, IS 12933 parts 1, 2, 3, 4, 5. New Delhi: Bureau of Indian Standards, Government of India; 2003.
[82] MNRE. Design and implementation of new financing mechanisms and instruments for promotion of solar water heating systems in India. Ministry of New and Renewable Energy, Government of India; 2010, http://www.mnre.gov.in/pdf/swhs-financingmech.pdf.
[83] MNRE. Salient features of solar water heating system. Ministry of New and Renewable Energy, Government of India; 2010, http://www.mnre.gov.in/swhs-features.htm.
[84] MNRE. MNRE 2010h Expected electricity and monetary savings from a 100 LPD DSHWS; 2010, http://www.mnre.gov.in./faq.
[85] Anand D. Solar water heating systems in India. Energy Sustain Dev 1994;1:51–7.
[86] TERI. TERI energy data and directory yearbook (TEDDY) 2003/2004. New Delhi: The Energy and Resources Institute; 2004.
[87] MNRE. List of BIS approved manufacturers of FPC based solar water heating systems. Ministry of New and Renewable Energy, Government of India; 2010, http://www.mnre.gov.in/list/list-fpc-m.htm.
[88] MNRE. Annual report. New Delhi: Ministry of New and Renewable Energy, Government of India; 2006.
[89] MNES. Annual report. New Delhi: Ministry of Non-Conventional Energy Sources, Government of India; 2005.
[90] MNRE. Jawaharlal Nehru National Solar Mission towards building solar India. Ministry of New and Renewable Energy, Government of India; 2010, http://mnre.gov.in/pdf/mission-document-JNNSM.pdf.
[91] Chandrasekhar B, Kandpal TC. An opinion survey based assessment of renewable energy technology development in India. Renew Sustain Energy Rev 2007;11.
[92] MNRE. Annual achievement for 2010–2011 and cumulative achievements as on 30-06-2010. Ministry of New and Renewable Energy, Government of India; 2010, http://www.mnre.gov.in.
[93] OPETTERI. Status of solar thermal technologies and markets in India and Europe; 2006, http://www.teri.res.in/teriin/opet/reports/solarthermal.pdf.
[94] Painuly JP, Gadgil A, Natarajan TV. Socio-economic constraints on the design of solar domestic hot-water systems for India. Energy 1987;12:85–96.
[95] Reddy BS. Barriers to the diffusion of renewable energy technologies – a case study of the state of Maharashtra, India. Roskilde, Denmark: UNEP Collaborating Centre on Energy and Environment, Riso National Laboratory; 2001.
[96] Reddy S, Painuly JP. Diffusion of renewable energy technologies – barriers and stakeholders' perspectives. Renew Energy 2004;29:1431–47.
[97] Sidiras DK, Koukios EG. Solar systems diffusion in local markets. Energy Policy 2004;32:2007–18.
[98] Chandrasekhar B, Kandpal TC. Effect of financial and fiscal incentives on the effective capital cost of solar energy technologies to the user. Sol Energy 2005;78:145–56.
[99] Sunderasan S. Policy support for the evolving solar water heating industry. Refocus 2006;7:46–9.
[100] Rannels J. The DOE office of solar energy technologies' vision for advancing solar technologies in the new millennium. Sol Energy 2000;69:363–8.
[101] Tsoutsos TD. Marketing solar thermal technologies: strategies in Europe, experience in Greece. Renew Energy 2002;26:33–46.
[102] Athanassios AA, Sevastianos M. The solar thermal market in Greece – review and perspectives. Renew Sustain Energy Rev 2003;7(5):397–418.
[103] Tsoutsos TD, Stamboulis YA. The sustainable diffusion of renewable energy technologies as an example of an innovation-focused policy. Technovation 2005;25:753–61.
[104] Rao KU, Ravindranath NH. Policies to overcome barriers to the spread of bio energy technologies in India. Energy Sustain Dev 2002;6:59–73.
[105] Ghosh D, Sagar AD, Kishore VV. Scaling up biomass gasifier use: an application-specific approach. Energy Policy 2006;34:1566–82.
[106] Gupta CL. Role of renewable energy technologies in generating sustainable livelihoods. Renew Sustain Energy Rev 2003;7:155–74.
[107] Pohekar SD, Soni MS, Ramachandran M. A review of wind energy developments in India. Int J Global Energy Issues 2004;21:276–86.
[108] Pohekar SD, Kumar D, Ramachandran M. Dissemination of cooking energy alternatives in India – a review. Renew Sustain Energy Rev 2005;9: 379–93.
[109] Pohekar SD, Ramachandran M. Multi-criteria evaluation of cooking energy alternatives for promoting parabolic solar cooker in India. Renew Energy 2004;29:1449–60.
[110] Pohekar SD, Ramachandran M. Hierarchical approach to evaluation and promotion of parabolic solar cookers in India. Energy Educ Sci Technol 2005;14:81–91.
[111] Malhotra P, Neudoerffer RC, Dutta S. A participatory process for designing cooking energy programmes with women. Biomass Bioenergy 2004;26:147–69.
[112] Painuly J. Barriers to renewable energy penetration; a framework for analysis. Renew Energy 2001;24:73–89.
[113] Roy B, Vincke P. Multicriteria analysis: survey and new directions. Eur J Oper Res 1981;8:207–18.